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The XMM-LSS Survey: Mapping hot, luminous, obscured and dark material out to $z \sim 1-2$

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Abstract. We review the unique cosmological implications of the XMM-LSS survey in association with its multi-λ follow-up: (1) Large Scale Structures traced by X-ray clusters and AGNs, optical galaxies, weak lensing as well as Sunyaev-Zel'dovich effect; (2) location of IR star forming galaxies and IR (obscured) AGNs within the cosmic web.
The XMM/MegaCam/VIRMOS/SIRTF data base will provide the first comprehensive study of structure formation - from hundreds of Mpc to galaxy scale - in close connection with environmental processes.

1 Introduction

The origin and evolution of the large-scale distribution of matter is a major cosmological issue. Although the universe appears homogeneous and isotropic on the largest scales, local galaxy surveys have revealed the existence of foam-like structure; galaxies are confined within sheets and filaments surrounding large "voids" with scales of 100 h^{-1} Mpc [2]. Galaxy clusters are usually located at the intersections of these sheets and filaments. Within the current theoretical hierarchical paradigm, structure originated in the very early universe and is observed directly at an early time via the cosmic microwave background (CMB) radiation. Density fluctuations were subsequently amplified by gravity and followed by the process of galaxy formation to produce the structure observed in the present epoch. The present-day "cosmic web" is therefore generated by the details of several key cosmological processes; the origin of structure, the nature and amount of dark matter, the nature of galaxy formation and the specific values of cosmological parameters. Observations of large-scale structure (LSS) therefore form a key element in our global understanding of the Universe.
The traditional method employed to study LSS is to map the galaxy distribution, either by covering very large coherent scales, e.g. the Sloan and 2dF surveys (several thousands of deg^2 out to $z_{max} \sim 0.1$ and 0.25 respectively), or probing evolution to significant depths like deep pencil beams and the forthcoming VIRMOS survey ($z_{max} \sim 1$ over a few deg^2). While providing strong constraints on models for structure formation, this approach is extremely data-intensive (from 150 000 galaxy spectra for VIRMOS to 10^6 for Sloan) and the interpretation depends both on global cosmological parameter combinations and on the details of galaxy formation, the latter still poorly defined. Another approach is to use QSOs: since they constitute the most luminous objects in the Universe, they can be observed up to very high redshift. However, data interpretation is even harder, as the link between galactic nuclear activity and initial mass fluctuations is currently not understood.
Alternatively, clusters of galaxies - the most massive entities in the Universe - offer considerable advantages both because they can provide complete samples of objects over a very large volume of space and because they are in some respects "simpler" to understand. The matter halos of clusters are easily traced by their X-ray emission (luminosity, size) while the theory describing their formation (biasing) and evolution from the initial fluctuations is well tested by N-body simulations. Such a level of understanding does not exist for galaxy and even less for QSO formation. Studies of cluster LSS and cluster abundances are powerful tools to constrain cosmological parameter values, independently of CMB and SN studies, as they do not rely on the same processes. In particular, they can break the degeneracy between the shape of the power spectrum and the matter density in addition to constraining

the validity of fundamental assumptions of the standard paradigm, for example, that LSS grows only by gravity.

Currently, the normalizations of the power spectra of structures traced by different objects are significantly different. Can all these results be consistent with a single Gaussian power spectrum for mass fluctuations, how do normalizations change with scales, what is the physical meaning of the normalization constants?

We have designed a comprehensive project with the observational goal of mapping the distribution of matter over a large volume out to redshifts $\sim 1-2$ using three complementary techniques: (1) X-ray observations to locate galaxy clusters and QSOs; (2) optical observations to obtain the galaxy distribution and to locate dark matter through a weak lensing analysis; and (3) Sunyaev-Zel'dovich effect observations to measure the distribution of diffuse extragalactic hot gas.

2 The XMM Large Scale Structure survey

Clusters of galaxies are thought to be the largest virialized entities in the universe. In the cosmic network picture, cluster formation occurs by matter accretion along the filaments so that the dynamical state of clusters is a permanent competition between accretion and relaxation processes, which act at rates that depend strongly on the embedding cosmology. Within clusters, the masses of individual galaxies are negligible, since dark matter accounts for $\sim 80\%$ of the mass and most of the rest is gas at a temperature of several $\times 10^7$ K which emits in the X-ray band. Averaged properties of X-ray clusters can be much more easily simulated and modelled than the galaxies they contain. For instance, a correlation exists between mass and X-ray luminosity for nearby clusters [8], which will certainly be investigated at high redshifts with up-coming deep XMM observations. X-ray clusters are also easy to find. An X-ray medium sensitivity survey at high galactic latitude essentially shows two types of objects: galaxy clusters (extended) and QSOs (pointlike). As it virtually eliminates projection effects, it is a vital complement to optical/NIR searches for (high redshift) clusters. Combined with optical spectroscopy, the whole provides the only comprehensive mapping of the large scale distribution of the deepest potential wells in the Universe and of AGNs. Exploiting the unrivalled sensitivity of XMM, the XMM-LSS will be ~ 1000 times deeper than the REFLEX survey [1]: with a sensitivity of $\sim 3 \times 10^{-15}\,\mathrm{ergs\,s^{-1}cm^{-2}}$ for point sources in the [0.5-2] keV (95% completeness level , [10]), we expect ~ 300 sources per deg^2. Out of them, approximately 15-20 clusters, 200 AGNs, with the remainder being stars and nearby galaxies.

Spanning 8×8 deg^2, the XMM-LSS survey will probe co–moving transverse scales of ~ 320 and 506 h^{-1} Mpc at redshifts $z = 1$ and $z = 2$ respectively. Approximately 900 clusters/groups will be identified out to $z = 1$ (ΛCDM, Fig. 1) and will enable the first investigation of the evolution of the cluster correlation function in two redshift bins [0-0.5] & [0.5-1]. The survey design is constrained by the requirement to obtain 15% precision in the estimated correlation length in each redshift bin. The low redshift bin will sample the cluster population over a smaller region than REFLEX but down to much lower-mass groups. The high-z bin will provide the first measurement of the cluster correlation function at these redshifts, and will enable a direct comparison with the low-z correlation function of massive clusters by REFLEX. The expected accuracy for the cosmological parameters, Ω_M, σ_8, and Γ will be 15%, 10% and 35% respectively. The XMM-LSS will also systematically explore the existence of massive clusters to redshifts $z \sim 2$ – a new, exciting territory. Though a handful of clusters are known around $z \sim 1.2$, properties and the state of equilibrium remain in the realm of speculation beyond $z > 1.5$. The constraints on cosmology expected from the entire XMM-LSS cluster study are summarized in Fig. 1 and discussed in detail by [7].

More than 200 Active Galactic Nuclei/QSOs are expected per square degree at the proposed XMM-LSS sensitivity, with half of these at $z < 1$ [3] and, in total, a space density 6 times higher than 2dF QSOs. This will provide the first complete deep sample of X-ray QSOs over a large coherent volume of the Universe and, consequently, an essential basis for comparison with optical clustering studies (e.g. 2dF, Sloan) on scales ranging from a few hundreds of pc to hundreds of Mpc. Together with a high S/N correlation function, we shall study the location of QSOs within the filament network defined by the cluster/group population as a function of the QSOs' X-ray and optical properties. This is crucial for our understanding of galactic nuclear activity in terms of peculiar initial density perturbations, environment conditions, and local galaxy interaction rate as well as to address the debated QSO

lensing issue.
The XMM-LSS will also provide first clues about the existence and the properties and space distribution of super clusters of galaxies in the distant universe.
Further important issues in cluster and QSO multi-wavelength evolution will be also addressed by the survey. Although in principle this could be achieved by XMM serendipitous pointings, the XMM-LSS Legacy data set will readily possess the advantage of uniform X-ray coverage and complete high quality optical imaging and spectroscopy. The scientific issues are reviewed in detail by [5] and [6].

3 Optical, radio and infra-red follow-up

The imaging of the 8×8 deg^2 XMM-LSS area is the priority target of the Canada-France-Hawaii Legacy Survey[1]. MegaCam, the one degree field image built by CEA to be installed at the new CFHT prime focus, will come into operation by mid-2002. It will provide the deep high quality optical multi-color imaging counterpart of the X-ray sources (u*=25.5, g'=26.8, r'=26.0, i'=25.3, z'=24.3) at a rate of 15 deg^2/yr in at least three colours. In particular, an optical cluster catalogue is currently under construction employing the CFH12k (then MegaCam) data using both spatial clustering analysis and multi-color matched filter techniques in addition to providing photometric redshift estimates. Moreover, the MegaCam data will form the basis of a weak lensing analysis[2], whose cosmological constraints will be compared to that provided by the X-ray data on the same region. This will be the first, coherent study on such scales. We have also R and z' imaging from CTIO. Data pipelines and processing have been developed by the TERAPIX[3] consortium; this will provide object catalogues and astrometric positions for the entire surveyed region. In addition, deep NIR VLT imaging (J, H, K) of $1 < z < 2$ cluster candidates found in in the XMM-LSS will be performed in order to confirm their reality prior to spectroscopy.
The standard spectroscopic follow-up will perform redshift measurements for all identified $0 < z < 1$ X-ray clusters in Multi-Object-Spectroscopy mode, mainly using NTT/EMMI and VLT/VIMOS. We plan to take 1 mask per cluster, randomly sampling the AGN population at the same time, the underlying filamentary galaxy distribution connecting clusters, radio sources from our VLA survey as well as, possibly, a representative sample of the SWIRE sources. This mapping around $0 < z < 1$ clusters will have an enormous scientific potential for studies of galaxy environments and bias. We shall subsequently undertake programmes of advanced spectroscopy (TNG, Las Campanas, CFHT, AAT, WHT, 2×Gemini, Magellan, LBT, VLT) that will focus on individual objects, and include high resolution spectroscopy, the measurement of cluster velocity dispersions, QSO absorption line surveys, as well as NIR spectroscopy of our $z > 1$ cluster candidates.
In the radio waveband the complete survey region is being mapped using the VLA at 74MHz and 325MHz. Radio coverage is not only particularly relevant for tracing merger events triggered by structure formation, but also a useful indicator of galactic nuclear or star–formation activity.
Sunyaev-Zel'dovich observations (S-Z) are also planned. Clusters in the XMM-LSS field will be targets of the prototype OCRA (One-Centimeter Radiometer Array) instrument from 2002. The full XMM-LSS field will be mapped by the complete OCRA, and will be an early target of the Array for Microwave Background Anisotropy (AMiBA) after 2004 [4]. This will enable a statistical analysis of the physics of the ICM as a function of redshift. In the long term these observations will also provide invaluable information on the low density structures such as cluster outskirts and their connections to the cosmic filaments. These measurements are complementary to the X-ray and weak lensing data regarding the masses of clusters and the structure of the hot gas they contain. The three data sets together should provide a direct and independent check of the extragalactic distance scale.
In the infrared, the SWIRE[4] SIRTF Legacy Programme will cover 10 deg^2 of the XMM-LSS in 7 wavebands from 4 to 160 mm. The estimated IR source numbers in this area are around 20000/900/250 and 700/50/500 for starbursts/spiral-irregular/AGN in the $0 < z < 1$ and $1 < z < 2$ redshift intervals respectively. This represents a unique X-ray/IR combination in depth and scales to be probed. The coordinated SWIRE/XMM-LSS observations will clarify an important aspect of environmental studies: how star formation in cluster galaxies depends on the distance to the cluster centre, on the strength of

[1] http://cdsweb.u-strasbg.fr:2001/Instruments/Imaging/Megacam/MSWG/forum.html
[2] http://www.iap.fr/LaboEtActivites/ThemesRecherche/Lentilles/LentillesTop.html
[3] http://terapix.iap.fr
[4] http://www.ipac.caltech.edu/SWIRE

the gravitational potential, and on the density of the ICM (as inferred from the X-ray data). In this respect the XMM-LSS represents the optimum SWIRE field, where galaxy environment, deep NIR imaging and optical spectroscopic properties will be the main parameters in modelling the MIR/FIR activity. Here also, the location of IR AGNs within the cosmic web will help establish their nature. The FIR/X/optical/radio association will also provide unique insights into the physics of heavily obscured objects as well as the first coherent study of biasing mechanisms as a function of scale and cosmic time for X-ray hot (XMM), dark (weak lensing), luminous galactic (optical/NIR) and obscured (SWIRE) material.
In summary, the XMM-LSS multi-λ data set will offer the first evolving view of structure formation from Mpc to galaxy scales. Its comprehensive approach constitutes a decisive new step in the synergy between space and ground-based observatory resources and therefore a building block of the forthcoming Virtual Observatory.

4 Survey layout

The overall survey design is a compromise between the cosmic scale to be probed, the volume that must be surveyed to detect enough clusters to measure cosmological parameters at a significant new level of accuracy (see Sec. 2, Fig. 1), and the total XMM exposure time.
The LSS Survey location is equatorial and has been carefully chosen based on X/optical/IR visibility criteria: it is a square area centered around $\alpha = 2^{\mathrm{h}}20^{\mathrm{m}}$, $\delta = -5^{\circ}$ (at $b = -58^{\circ}$, with neutral hydrogen column $2 \times 10^{20} < N_H/\mathrm{cm}^{-2} < 5 \times 10^{20}$). This area surrounds two deep XMM surveys based on guaranteed time: the XMM_SSC/Subaru Deep Survey (80 ks exposures in 1 deg^2) and the XMM Medium Deep survey (XMDS; 20 ks exposures in 2 deg^2), the latter being a collaboration between several Co-Is of the present proposal; XMM: Liège(OM), Milan-IFCTR(EPIC), Saclay(SSC); MegaCam(Saclay, IAP); VIRMOS(France/Italy). The area overlap will greatly assist in the study of selection effects.
The first release of the XMM-LSS reduced data set will occur by mid-2003 and will be subsequently updated on a yearly basis as the X-ray coverage and associated optical follow-up proceed.

5 More information

is available at the XMM-LSS web page:
http://vela.astro.ulg.ac.be/themes/spatial/xmm/LSS/index_e.html

References

[1] Böhringer H., Schuecker P., Guzzo L., Collins C. A., Voges W., Schindler S., Neumann D. M., Cruddace R. G., De Grandi S., Chincarini G., Edge A. C., MacGillivray H. T., Shaver P., 2001, A&A 369, 826

[2] Landy S.D. et al., 1996, ApJ 456, L1

[3] Lehman et al. 2001 A& A 371, 833

[4] Liang H., 2001, astro-ph/0110518

[5] Pierre M., 2000, in "Mining the Sky", ESO Astr. Symp., Ed. Banday et al., p. 185

[6] Pierre M., 2001, ESO Messenger September issue 105, p32

[7] Refregier A, Valtchanov I, Pierre M, 2001, astro-ph/0109529.

[8] Reiprich T. H. & Böhringer H., 1999, astroph/9909035 and Astron. Nachr. 320, 296

[9] Starck J.L., Pierre M., 1998, A&A 128, 397

[10] Valtchanov I., Pierre M., Gastaud R., 2001, A&A 370, 689

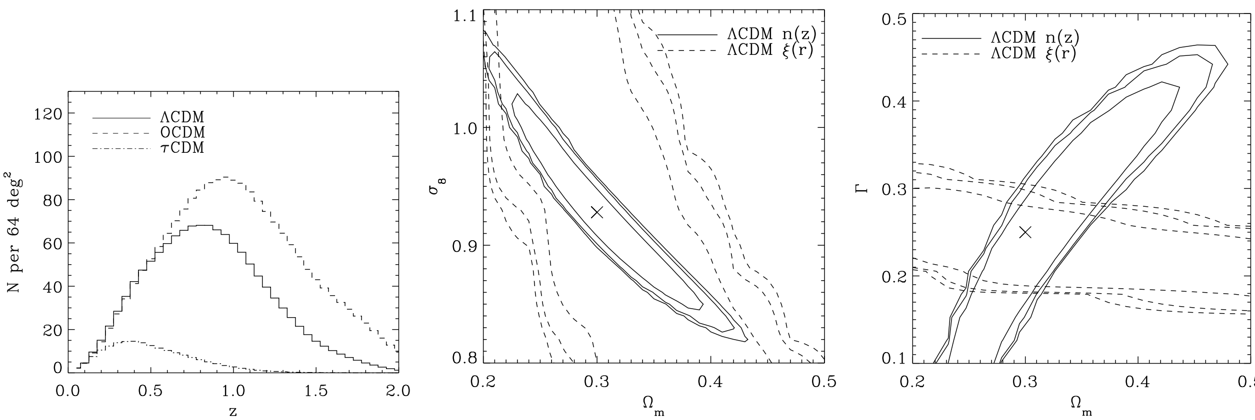

Figure 1: **Cosmological constraints from the XMM-LSS**(from [7]).
Left: The predicted XMM-LSS cluster redshift distribution generated by various cosmological models. The selection function for the XMM-LSS, generated by extensive image simulations, was employed to construct each model. Note that, current favoured values have been assumed here for ΛCDM, but the predicted number of objects strongly depends on the assumed value of the cosmological parameters (Fig. 7 of [7]); **Centre:** Constraints upon the cosmological parameters Ω_m and σ_8 (the amplitude of mass fluctuations on 8 h^{-1} Mpc scale) for a ΛCDM universe obtained from XMM-LSS cluster counts (solid lines) and correlation function (dashed lines). In each case, the 68%, 90% and 95% confidence level contours are shown along with the assumed model (cross). Cluster abundance data provides strong constraints upon the $\Omega_m - \sigma_8$ combination. **Right:** Constraints upon the cosmological parameters Γ (the shape of the power spectrum) and Ω_m for a ΛCDM universe (symbols as defined in **Centre**). The correlation function is a powerful tool to constrain the shape of the initial spectrum. These calculations have been performed assuming that only the redshifts over the $[0 < z < 1] \times [64$ deg$^2]$ volume are available.

In addition, identification of a "Coma–type" cluster within the XMM-LSS over the redshift range $1.5 < z < 2$ has a probability of $\sim 6.5 \times 10^{-7}$ in the current ΛCDM scenario. Therefore, any such discoveries in the survey would put the currently favoured cosmological model in great observational difficulty.